



Figure 10. Hydraulic head contours and capture zones simulated using TWODAN (Fitts, 1995) for several extraction/injection schemes in an aquifer with a uniform transmissivity of $1000 \text{ ft}^2/\text{d}$, and an initial hydraulic gradient of 0.01. Pathline time intervals of one year are marked by arrows. Note the stagnation zones that develop downgradient of extraction wells and upgradient of injection wells.

contamination zone, minimize stagnation zones, flush pore volumes through the system, and contain contaminated ground water. Wells are installed in lines and other patterns to achieve these objectives (Figure 10). Horizontal wells and drains are constructed to create ground-water line sinks and mounds, and thereby affect linear hydraulic sweeps.

Pore Volume Flushing

Restoration requires that sufficient ground water be flushed through the contaminated zone to remove both existing dissolved contaminants and those that will continue to desorb from porous media, dissolve from precipitates or NAPL, and/or diffuse from low permeability zones. The sum of these processes and dilution in the flow field yields persistent acceptable ground-water quality at compliance locations.

The volume of ground water within a contamination plume is known as the pore volume (PV), which is defined as

$$PV = \int_A b n dA \quad (1)$$

where b is the plume thickness, n is the formation porosity, and A is the area of the plume. If the thickness and porosity are relatively uniform, then

$$PV = BnA \quad (2)$$

where B is the average thickness of the plume.

Assuming linear, reversible, and instantaneous sorption, no NAPL or solid contaminants, and neglecting dispersion, the theoretical number of PVs required to remove a contaminant from a homogeneous aquifer is approximated by the retardation factor, R , which is the ground-water flow velocity relative to velocity of dissolved contaminant movement. An example of the relationship between the number of PVs and R , that also accounts for dispersion, is demonstrated by a numerical model used to evaluate a P&T design at the Chem-Dyne site in Ohio (Ward et al., 1987). Due to simulation of linear sorption, a nearly linear relationship was found to exist between retardation and the duration of pumping (or volume pumped) needed to reach the ground-water clean-up goal. Batch flush models (e.g., U.S. EPA, 1988b; Zheng et al., 1992) often assume linear sorption to calculate the number of PVs required to reach a clean-up concentration, C_{wt} in ground water as a function of the retardation factor, R , and the initial aqueous-phase contaminant concentration, C_{wo} :

$$\text{No. of PVs} = -R \ln (C_{wt} / C_{wo}) \quad (3)$$

Though useful for simple systems, the representation of linear, reversible, and instantaneous sorption in contaminant transport models can lead to significant underestimation of P&T clean-up times. For example, the desorption of most inorganic contaminants (e.g., chromium and arsenic) is nonlinear. In addition, much of the pore space in aquifer materials may not be available for fluid flow. In such situations, flushing is not efficient and removal of a greater number of pore volumes of water will be required.

Kinetic limitations often may prevent sustenance of equilibrium contaminant concentrations in ground water (Bahr, 1989; Brogan,

1991; Haley et al., 1991; Palmer and Fish, 1992). Such effects occur in situations where contaminant mass transfer to flowing ground water is slow relative to ground-water velocity. For example, contaminant mass removal from low permeability materials may be limited by the rate of diffusion from these materials into more permeable flowpaths. In this situation, increasing ground-water velocity and pore volume flushing rates beyond a certain point would provide very little increase in contaminant removal rate. Kinetic limitations to mass transfer are likely to be relatively significant where ground-water velocities are high surrounding injection and extraction wells.

The number of PVs that must be extracted for restoration is a function of the clean-up standard, the initial contaminant distribution, and the chemical/media phenomena that affect cleanup. Screening-level estimates of the number of PVs required for cleanup can be made by modeling and by assessing the trend of contaminant concentration versus the number of PVs removed. At many sites, numerous PVs (i.e., 10 to 100s) will have to be flushed through the contamination zone to attain clean-up standards.

The number of PVs withdrawn per year is a useful measure of the aggressiveness of a P&T operation. Many current systems are designed to remove between 0.3 and 2 PVs annually. For example, less than 2 PVs per year were extracted at 22 of the 24 P&T systems studied by U.S. EPA (1992b) and reviewed by NRC (1994). Low permeability conditions or competing uses for ground water may restrict the ability to pump at higher rates. As noted above, kinetic limitations to mass transfer also may diminish the benefit of higher pumping rates. The potential significance of such limitations should be evaluated prior to installation of aggressive systems designed for relatively high flushing rates. If limiting factors are not present, pumping rates may be increased to hasten cleanup.

The time required to pump one pore volume of ground water from the contaminated zone is a fundamental parameter that should be calculated for P&T systems. NRC (1994), however, determined that the number of PVs withdrawn at P&T sites is rarely reported. Restoration assessments should include estimates of the number of PVs needed for cleanup. However, it must be noted that such analyses generally oversimplify highly complex site conditions. It may often be impracticable to characterize the site in sufficient detail to reduce uncertainty in estimates of restoration time frames to insignificant levels. Uncertainty in these estimates should be considered during remedial evaluations.

Poor P&T design may lead to low system effectiveness and contaminant concentration tailing. Poor design factors include low pumping rates and improper location of pumping wells and completion depths. A simple check on the total pumping rate is to calculate the number of PVs per year. Inadequate location or completion of wells or drains may lead to poor P&T performance even if the total pumping rate is appropriate. For example, wells placed at the containment area perimeter may withdraw a large volume of clean ground water from beyond the plume via flowlines that do not flush the contaminated zone. Similarly, pumping from the entire thickness of a formation in which the contamination is limited vertically will reduce the fraction of water that flushes the contaminated zone. In general, restoration pumping wells or drains should be placed in areas of relatively high contaminant concentration as well as locations suitable for achieving hydraulic containment.